Cosmic transparency: A test with the baryon acoustic feature and type Ia supernovae

Surhud More[1,2], Jo Bovy[3], and David W. Hogg[1,3]

ABSTRACT

Conservation of the phase-space density of photons plus Lorentz invariance requires that the cosmological luminosity distance be larger than the angular diameter distance by a factor of $(1+z)^2$, where z is the redshift. Because this is a fundamental symmetry, this prediction—known sometimes as the "Etherington relation" or the "Tolman test"—is independent of the world model, or even the assumptions of homogeneity and isotropy. It depends, however, on Lorentz invariance and transparency. Transparency can be affected by intergalactic dust or interactions between photons and the dark sector. Baryon acoustic feature (BAF) and type Ia supernovae (SNeIa) measures of the expansion history are differently sensitive to the angular diameter and luminosity distances and can therefore be used in conjunction to limit cosmic transparency. At the present day, the comparison only limits the change $\Delta\tau$ in the optical depth from redshift 0.20 to 0.35 at visible wavelengths to $\Delta\tau < 0.13$ at 95% confidence. In a model with a constant comoving number density n of scatterers of constant proper cross-section σ, this limit implies $n\,\sigma < 2\times10^{-4}\,h$ Mpc^{-1}. These limits depend weakly on cosmological world model. Assuming a concordance world model, the best-fit value of $\Delta\tau$ to current data is negative at the 2σ level. This could signal interesting new physics or could be the result of unidentified systematics in the BAF/SNeIa measurements. Within the next few years, the limits on transparency could extend to redshifts $z\approx2.5$ and improve to $n\,\sigma < 1.1\times10^{-5}\,h$ Mpc^{-1}. Cosmic variance will eventually limit the sensitivity of any test using the BAF at the $n\,\sigma\sim4\times10^{-7}\,h$ Mpc^{-1} level. Comparison with other measures of the transparency is provided; no other measure in the visible is as free of astrophysical assumptions.

Subject headings: cosmology: observations — cosmology: fundamental parameters — large-scale structure of universe — radiative transfer — relativity — supernovae: general

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[1] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

[2] To whom correspondence should be addressed: `more@mpia-hd.mpg.de`

[3] Center for Cosmology and Particle Physics, Department of Physics, New York University, 4 Washington Place, New York, NY 10003

1. Introduction

The transparency of the universe is extremely good. A typical astronomical camera has a shutter whose thickness is measured in microns; that shutter is far more opaque than the entire line of sight to the majority of extragalactic sources, even at extremely high redshifts, despite—in many cases—considerable column depths of dark matter, plasma, gas, and dust. There are, however, very few quantitative measures of the transparency with contemporary astronomical data.

There are several sources for photon attenuation that are clustered with matter. For example, as stars eject heavy elements, they also eject photon-absorbing ash (called "dust"). The gas and plasma in and around galaxies absorbs, scatters, and re-emits at longer wavelengths some fraction of incident radiation. More speculatively, if the dark matter is an axion or axionlike particle, it will in general have photon interactions, which can in principle produce effective absorption of photons in regions of high dark matter density and high magnetic fields (Sikivie 1983; Raffelt & Stodolsky 1988). The sources of attenuation—such as these—that are clustered with matter will be correlated with galaxies and large-scale structure, and can be found with "angular difference" measurements that compare the apparent properties of sources whose lines of sight have different impact parameters with the correlated structure.

The Sloan Digital Sky Survey has permitted very sensitive angular difference measurements, which find that the attenuation correlated with large-scale structure is very small and consistent with being caused by dust, presumably the dust emitted by the stars in the galaxies that populate the structure. Measurements in the literature constrain this in visible bandpasses at the part in 10^3 level (Ménard *et al.* 2008; Bovy *et al.* 2008). To be specific, these studies constrain *differences* in opacity along different lines of sight caused by absorbers correlated with galaxies.

It is possible, however, that there might be unclustered or "monopole" sources of attenuation, that affect all lines of sight equally, for example if the nonmatter contributors to the cosmological energy−momentum tensor (the "dark energy" in modern parlance) have interactions with photons, or if there are small violations of Lorentz invariance on cosmological scales. These sources of attenuation are much harder to detect with differential experiments, but they *can* be detected by "radial difference" experiments that compare cosmological sources of radiation of known physical properties at different redshifts or radial distances.

A number of different mechanisms have been proposed during the last decade to explain the observed dimming of type Ia supernovae (SNeIa; Riess *et al.* 1998; Perlmutter *et al.* 1999) without cosmic acceleration by employing exactly such unclustered sources of attenuation. The mixing of photons with axions in extragalactic magnetic fields could lead to photons oscillating into axions with a non-negligable probability over cosmological distances, thus reducing the flux of SNeIa at large distances (Csáki, Kaloper & Terning 2002). Alternatively, "gray" intergalactic dust could be so gray as to evade detection through its *reddening*, while still being cosmologically important because of its overall *opacity* (Aguirre 1999). In order to account for the observed SNeIa dimming, these models predict violations of transparency at the order-unity level out to redshifts of unity

(*e.g.*, Mörtsell, Bergström, & Goobar 2002).

Furthermore, even if there are no exotic absorbers in the universe, it is difficult (and usually model dependent) to infer the total mean opacity from any absorbers that have been found by angular difference experiments. Radial difference and angular difference experiments are complementary, even when the absorbers are mundane; although radial difference experiments are usually less precise, they provide irreplaceable information for measuring total opacity.

Radial difference experiments are sometimes known as "Tolman tests" because they are variants of the test proposed by Tolman (1930) of the expansion of the universe: a test of the $(1+z)^{-4}$ (where z is the redshift) dimming of bolometric intensity (energy per unit time per unit area per unit solid angle; also called "bolometric surface brightness") with redshift. The intensity is closely related to the phase-space density of photons, which is conserved (in a transparent medium) along the light path; that conservation plus Lorentz invariance implies the $(1+z)^{-4}$ relation: one factor of $(1+z)^{-1}$ comes from the decrease in energy of each photon due to the redshift, another factor comes from the decrease in photons per unit time, and two more factors arise from the solid-angle effects of relativistic aberration. The Tolman test does not really test for the expansion of the universe—the result does not depend on cosmological model, or even assumptions of isotropy or homogeneity—but rather for the combination of conservation of photon phase-space density and Lorentz invariance.

In addition to models that violate transparency, there are models that violate Lorentz invariance. Generically these models produce an energy-dependent speed of light and birefringence, breaking the perfect nondispersiveness of the vacuum (Amelino-Camelia *et al.* 1998; Gambini & Pullin 1999). These effects generally become larger with increasing energy, and observations of high-energy sources such as active galactic nuclei (Biller *et al.* 1999; Aharonian *et al.* 2008; Albert *et al.* 2008) and gamma-ray bursts (GRBs; Schaefer *et al.* 1999; Ellis *et al.* 2006) have shown that the linear dispersion relation for photons is preserved to good accuracy at these energies. Therefore, while these models do fail the Tolman test because of their nontrivial dispersion relations, the effect will be unmeasurably small for low-energy (visible-band) photons.

By far the most precise radial difference test to date has been performed in the radio with the cosmic background radiation. In contemporary cosmological models, the CBR comes from redshift ~ 1100 and is a near-perfect blackbody. The COBE DMR experiment established that the spectrum and amplitude of this radiation are consistent with the blackbody expectation at the $< 10^{-2}$ level at 95% confidence (Mather *et al.* 1994). A source of attenuating material, unless in perfect thermal equilibrium with the CBR, would tend to change either the spectrum or the amplitude, so this result provides a very strong constraint on the transparency at cm wavelengths (Mirizzi *et al.* 2005). Another test of transparency at cm wavelengths is the increase in the CMB temperature $T_{\rm CMB}$ according to the relation $T_{\rm CMB} \propto (1+z)$. Srianand *et al.* (2000) find consistency with a transparent universe by measuring the CMB temperature at $z = 2.3$. Of course, many sources of attenuation are expected to be wavelength dependent, so these beautiful results may not strongly

constrain the opacity in the visible.

At visible wavelengths, there have been much less precise radial difference tests performed with galaxies, whose properties would deviate from naive predictions under extreme attenuation. After correcting for the evolution of stellar populations in galaxies, these studies find consistency with transparency at the 0.5 mag level at 95% confidence (Pahre *et al.* 1996; Lubin & Sandage 2001), which correspond to optical depth limits < 0.5 out to redshift $z \sim 1$. Unfortunately, the precision of these tests is not limited by the precision of the measurements, but rather by the precision with which the evolution of galaxy stellar populations is known; the results will not be improved substantially with additional or more precise observations.

Another test of transparency at visible wavelengths involves the measurement of the Cosmic Infrared Background (hereafter CIB). The absorption of visible photons by a diffuse component of intergalactic dust and its re-emission in the infrared contributes to the CIB. The amount of dust required to explain the systematic dimming of SNeIa would produce most of the observed CIB (Aguirre & Haiman 2000). However, discrete sources (*e.g.*, dusty star-forming galaxies) also emit in the infrared and account for almost all of the CIB, strongly constraining the role of dust in the dimming of SNeIa. Any constraint on the transparency from the CIB requires a careful subtraction of the discrete sources (Hauser & Dwek 2001).

The Tolman test can be rewritten as a relationship among cosmological distance measures. There are several empirical definitions of distance in cosmology (*e.g.*, Hogg 1999); the most important for contemporary observables are the luminosity distance $D_{\rm L}$ and the angular diameter distance $D_{\rm A}$. The luminosity distance $D_{\rm L}$ to an object is defined to be the distance that relates bolometric energy per unit time per unit area S (flux) received at a telescope to the energy per unit time L (luminosity or power) of the source, or

$$S = \frac{L}{4\pi\, D_{\rm L}^2} \quad . \tag{1}$$

The angular diameter distance $D_{\rm A}$ is the distance that relates the observed (small) angular size Θ measured by a telescope to the proper size R of an object, or

$$\Theta = \frac{R}{D_{\rm A}} \quad . \tag{2}$$

Because the ratio of flux to the solid angle is essentially the intensity, the $(1+z)^{-4}$ redshift dependence of the intensity is reflected in these distance measures by

$$D_{\rm L} = (1+z)^2\, D_{\rm A} \quad . \tag{3}$$

Both distance measures are strong functions of the world model, but this relationship between them—known sometimes as the "Etherington relation" (after Etherington 1933, who showed that the result is valid in arbitrary spacetimes)—depends only on conservation of phase-space density of photons (transparency) and Lorentz invariance. Fortunately, for some fortuitous types of objects, these distances can be measured nearly independently.

A test of this type for transparency has been proposed and carried out previously (Bassett & Kunz 2004a,b), with luminosity distances from SNeIa and angular diameter distances estimated from FRIIb radio galaxies, compact radio sources, and X-ray clusters (Uzan *et al.* 2004; Jackson 2008). The results were imprecise because there are many astrophysical uncertainties in the proper diameter estimates of these exceedingly complex astrophysical sources.

In the contemporary adiabatic cosmological standard model, there is a feature in the dark-matter autocorrelation function (or the power spectrum) corresponding to the communication of density perturbations by acoustic modes during the period in which radiation dominates (Peebles & Yu 1970; Eisenstein *et al.* 2005). This feature has a low amplitude in present-day structure (that is, the distribution of galaxies), but because it evolves little in comoving coordinates, it provides a "standard ruler" for direct measurement of the expansion history. A measurement of the baryon acoustic feature (BAF) in a population of galaxies at a particular redshift provides a combined measure of the angular diameter distance to that redshift (from the transverse size of the feature) and the Hubble constant or expansion rate at that redshift (from the line-of-sight size of the feature). As we discuss below, as signal-to-noise improves, the BAF can be used to measure the angular diameter independently of the local Hubble rate. Most importantly, because the BAF arises from extremely simple physics in the early universe when the growth of structure is linear and electromagnetic interactions dominate, the BAF measures the angular diameter distance with far fewer assumptions than any method based on complex astrophysical sources in the highly nonlinear regime.

At the same time, SNeIa have been found to be standard—or really "standardizable"—candles, which can be used to make an independent direct measurement of the expansion history (Baade 1938; Tammann 1979; Colgate 1979; Riess *et al.* 1998; Perlmutter *et al.* 1999). Up to an overall scale and some uncertainties about the intrinsic spectra and variability among SNeIa, a collection of SNeIa measure the luminosity distance.

Given overall scale uncertainties, the most robust test of global cosmic transparency that can be constructed from these two distance indicators is a measurement of the ratio of the distances to two redshifts z_1 and z_2. That is, transparency requires

$$\frac{D_{\rm L}(z_2)}{D_{\rm L}(z_1)} = \frac{[1+z_2]^2}{[1+z_1]^2}\,\frac{D_{\rm A}(z_2)}{D_{\rm A}(z_1)} \quad . \tag{4}$$

This expression cancels out overall scale issues and is independent of the world model. We perform a very conservative variant of this test below, where we measure the left-hand side with SNeIa and the right-hand side with the BAF, marginalizing over a broad range of world models.

The tests presented here are not precise, simply because at the present day BAF measurements are in their infancy, and we make use of no cosmological data other than the BAF and SNeIa. As we discuss below, when these measurements are made at higher redshifts and with higher precisions, our limits on transparency and Lorentz invariance will improve by orders of magnitude. Eventually they may be limited not by the data quality but by the cosmic variance limit on the BAF measurement

itself (Seo & Eisenstein 2007).

2. Data, procedure, and results

In surveys to date, where the BAF is measured at low signal to noise, the optimal extraction of the signal best constrains not the angular diameter distance directly, but rather a hybrid distance $D_{\rm V}$

$$D_{\rm V} = \left[\frac{c\, z\, [1+z]^2\, D_{\rm A}^2}{H(z)} \right]^{1/3} \quad , \tag{5}$$

where $D_{\rm A}$ is the angular diameter distance and $H(z)$ is the Hubble expansion rate (velocity per unit distance) at redshift z (Eisenstein *et al.* 2005).

Using data from the Sloan Digital Sky Survey and the Two Degree Field Galaxy Redshift Survey, the power spectrum and BAF have now been measured in samples of massive, red galaxies at two different redshifts: $z = 0.20$ and $z = 0.35$. The measured BAF at each redshift z translates to a distance measure $D_{\rm V}(z)$. Accounting for covariances in the measurements at the two redshifts (which are not based on entirely independent data sets), the ratio of distances is $D_{\rm V}(0.35)/D_{\rm V}(0.20) = 1.812 \pm 0.060$ (68% confidence; Percival *et al.* 2007).

We formed two samples of SNeIa data from a recent compilation (Davis *et al.* 2007). "Sample A" consists of all seven SNeIa in the redshift range $0.15 < z < 0.25$ and "Sample B" consists of all 22 SNeIa in the redshift range $0.3 < z < 0.4$. We estimate the distance−modulus DM at $z = 0.20$ and $z = 0.35$ by fitting a straight line to Samples A and B separately (Figure 1), and obtain a distance−modulus difference

$$\Delta DM_{\rm obs} = DM_{\rm obs}(0.35) - DM_{\rm obs}(0.20) = [1.34 \pm 0.09]\ {\rm mag} \quad , \tag{6}$$

where we are indicating that this is an observed value, and might differ from the true value if there is opacity.

The distance modulus derived from the SNeIa is systematically affected by the presence of any intervening absorber. Let $\tau(z)$ denote the opacity between an observer at $z = 0$ and a source at redshift z due to such extinction effects. The flux received from this source is reduced by the factor ${\rm e}^{-\tau(z)}$. The inferred (observed) luminosity distance differs from the "true" luminosity distance:

$$D_{\rm L\,obs}^{2}(z) = D_{\rm L\,true}^{2}(z)\, {\rm e}^{\tau(z)} \quad . \tag{7}$$

The ratio of the luminosity distances at two different redshifts z_1 and z_2 depends upon the factor ${\rm e}^{[\tau(0.35)-\tau(0.20)]/2}$. The inferred (observed) distance modulus differs from the "true" distance modulus:

$$DM_{\rm obs}(z) = DM_{\rm true}(z) + [2.5\ \log e]\, \tau(z) \quad . \tag{8}$$

Taking differences of distance moduli at the two redshifts:

$$\Delta DM_{\rm obs} = \Delta DM_{\rm true} + [2.5\ \log e]\, \Delta\tau \quad , \tag{9}$$

where $\Delta\tau \equiv [\tau(z_2) - \tau(z_1)]$. If the distance indicator from the BAF is unaffected by the absorption as we expect, then

$$\Delta\tau = \frac{\ln(10)}{2.5}\left[\Delta DM_{\rm obs} - 7.5\,\log\left(\frac{D_{\rm V}(z_2)}{D_{\rm V}(z_1)}\right) + 2.5\,\log\left(\frac{z_2\,[1+z_1]^2\,H(z_1)}{z_1\,[1+z_2]^2\,H(z_2)}\right)\right] \quad . \tag{10}$$

The above equation can be used to determine $\Delta\tau$ from $z = 0.35$ to $z = 0.20$ in light of the ratio of the distances $D_{\rm V}$ obtained from the BAF observations (hereafter B) and the difference in distance moduli obtained from the SNeIa observations (hereafter S) at these redshifts. However, the last term in the above equation makes the result cosmology dependent. Therefore, we follow a Bayesian approach and assign posterior probabilities to 100 uniformly spaced values of $\Delta\tau \in$ [0,0.5] by marginalizing over 100×100 ΛCDM cosmologies uniformly spaced in the $(\Omega_\Lambda, \Omega_M)$ plane with $\Omega_\Lambda \in$ [0,1] and $\Omega_M \in$ [0,1]. Thus,

$$P(\Delta\tau|S,B) = \int_{\Omega_\Lambda}\int_{\Omega_M} P(\Omega_\Lambda,\Omega_M|B)\,P(\Delta\tau,\Omega_\Lambda,\Omega_M|S)\,{\rm d}\Omega_M\,{\rm d}\Omega_\Lambda \quad , \tag{11}$$

where $P(\Omega_\Lambda, \Omega_M|B)$ and $P(\Delta\tau, \Omega_\Lambda, \Omega_M|S)$ are the posterior probabilities of the set of model parameters given B and S respectively. We assume that the uncertainties on B and S are Gaussian and calculate the likelihood of B and S for different sets of parameters in the $(\Delta\tau, \Omega_\Lambda, \Omega_M)$ space. Assuming flat priors on Ω_Λ and Ω_M in the ranges $0 < \Omega < 1$, and flat prior on $\Delta\tau$ in the range $0 < \Delta\tau < 0.5$, the posterior probabilities $P(\Omega_\Lambda, \Omega_M|B)$ and $P(\Delta\tau, \Omega_\Lambda, \Omega_M|S)$ are calculated from the likelihoods of the two data sets. Equation (11) yields the posterior for $\Delta\tau$, marginalized over all world models. Figure 2 shows the posterior $P(\Delta\tau|S,B)$ for the difference in optical depths between redshifts 0.35 and 0.20 obtained from the procedure outlined above. The posterior peaks at 0 and yields $\Delta\tau < 0.13$ at 95% confidence. The result demonstrates the transparency of the universe between these two redshifts, although not at high precision.

The abundance and absorption properties of absorbers can be constrained using the difference in optical depths measured above. Let $n(z)$ denote the comoving number density of absorbers, each with a proper cross-section $\sigma(z)$ at redshift z. The difference in optical depths between redshifts z_1 and z_2 is then given by

$$\Delta\tau = \int_{z_1}^{z_2} n(z)\,\sigma(z)\,D_{\rm H}\,\frac{(1+z)^2}{E(z)}\,{\rm d}z \quad , \tag{12}$$

where $D_{\rm H}$ is c/H_0 and

$$E(z) \equiv \frac{H(z)}{H_0} = \sqrt{\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda} \quad . \tag{13}$$

In detail, the output of this integral depends on world model. For the concordance model, Hubble constant $H_0 = 100\,h\ {\rm km\,s^{-1}\,Mpc^{-1}}$, and assuming $n(z)$ and $\sigma(z)$ to be independent of redshift, $\Delta\tau$ measured between redshifts 0.35 and 0.20 constrains $n\,\sigma < 2 \times 10^{-4}\,h\ {\rm Mpc^{-1}}$ at 95% confidence.

A naive calculation of $\Delta\tau$ using Equation (10) for the concordance ΛCDM model ($\Omega_M = 0.258, \Omega_\Lambda = 0.742$) obtained from the analysis of the 5-year WMAP data (Dunkley *et al.* 2008),

yields $\Delta\tau = -0.30 \pm 0.26$ at 95% confidence. This shows that there is a slight tension between the results of current measurements of the BAF and of the SNeIa under the currently accepted world model. More generally, a similar tension, i.e., a brightening of the SNe, between measurements of the cosmological parameters by using standard rulers and standard candles has been reported before (Bassett & Kunz 2004a,b; Percival *et al.* 2007; Lazkoz *et al.* 2008). SNe brightening is not impossible in models that involve axion-photon mixing (Bassett & Kunz 2004b) or chameleon-photon mixing (Burrage 2008) if the corresponding particles are abundantly produced during SNeIa explosions. However, a negative value of $\Delta\tau$ could also indicate the presence of a systematic bias in the distance measurements based upon the SNeIa brightness or the BAF, *e.g.*, overcorrection for extinction in the host galaxy of the SNeIa brightnesses or magnification bias in the SNeIa selection (Williams & Song 2004). Note that the prior, $\Delta\tau > 0$, improves the magnitude of the uncertainty on $\Delta\tau$ (from 0.26 to 0.13). The 95% confidence interval shrinks with the prior because we sample only from the rapidly falling tail of the posterior.

3. Future Constraints

In the future, the constraints from both the SNeIa and the BAF observations will improve in accuracy and will cover a wider redshift range. The Baryon Oscillation Spectroscopic Survey (BOSS) is currently underway and plans to measure the BAF in luminous red galaxies at redshifts $z = 0.35$ and $z = 0.6$. The key improvements would be the larger redshift range and the power to resolve the BAF both in the line-of-sight direction (constrains H) and the transverse direction (constrains $D_{\rm A}$). This would remove the weak world-model dependence in our present analysis. The angular diameter distances to these redshifts would be measured to an accuracy of $\sim 1\%$ (http://www.sdss3.org/). In parallel, the Supernovae Legacy Survey (SNLS), when complete, expects ~ 700 SNeIa in the redshift range $0 < z < 1.7$ (Astier *et al.* 2006). The uncertainty on the estimate of the distance moduli to redshifts $z = 0.35$ and $z = 0.6$ will be roughly four times better with the increased numbers. Using the test of the duality relation described above, $\Delta\tau$ between $z = 0.35$ and $z = 0.6$ would be constrained to better than 0.07 (95% confidence), independent of the adopted cosmological model. The constraint on $n\,\sigma$ would become $n\,\sigma < 5.4 \times 10^{-5}\,h$ Mpc^{-1}.

BOSS will also use the Lyα forest in the spectra of bright quasi-stellar objects to measure the BAF at redshift $z \sim 2.5$ with an accuracy of ~ 1.5 percent. No current or planned SNeIa surveys expect to detect SNeIa at such a high redshift. However the highest redshift (~ 1.7) measurements of $D_{\rm L}$ from the SNLS could potentially be used in conjunction with the $D_{\rm A}$ measurement to get a constraint on the transparency of the universe by marginalizing over different world models. Interestingly, there have been recent efforts to calibrate GRBs as standard candles and to extend the Hubble diagram to higher redshifts (Liang *et al.* 2008). The SNeIa at low redshift and the GRBs at high redshifts can provide a measurement of the difference between the DM between redshifts 0.35 and 2.5. We optimistically assume that the difference in the DM to these redshifts can be measured with an accuracy of ~ 0.1 similar to the one obtained from the analysis of SNeIa at

$z = 0.2$ and $z = 0.35$ in Section 2. These measurements shall then constrain $\Delta\tau$ between redshifts 2.5 and 0.35 to an accuracy of 0.2 with 95 percent confidence. This translates into an accuracy on $n\,\sigma$ of $\sim 1.1 \times 10^{-5}\,h$ Mpc^{-1}.

In the optimistic future, the uncertainty on $D_{\rm L}(z)$ could, in the absence of damaging systematics, diminish arbitrarily as the number of observed SNeIa grows. However, the precision of any BAF measurement is limited by sample variance (the number of independent wavelengths of a given fluctuation that can fit in the finite survey volume is limited), even when the uncertainty caused by incomplete sampling of the density field (shot noise) is negligible (Seo & Eisenstein 2007). The sample variance error goes down with the square root of the volume of the survey. To calculate a representative limit, we consider an optimistic all-sky survey covering the redshift range $2.45 < z < 2.55$. Such a survey can be used to determine $D_{\rm A}(z = 2.5)$ to a fractional accuracy of ~ 0.004 (95% confidence). This will ultimately constrain the optical depth to redshift $z = 2.5$ to $\tau < 0.008$ and hypothetical absorbers to $n\,\sigma < 4 \times 10^{-7}\,h$ Mpc^{-1}.

4. Discussion

We have advocated and analyzed the expected future performance of a simple Tolman test or test of the Etherington relation, that is, that the luminosity distance is larger than the angular diameter distance by two powers $(1 + z)$, using SNeIa to measure the luminosity distance and the BAF to measure the angular diameter distance. We have shown that this test will eventually provide very precise measurements of the conservation of photon phase-space density.

We performed the test with the limited data available at the present day. We used only the ratio of distances at redshifts of $z = 0.20$ and 0.35 to remove uncertainties about the overall scale. We find consistency with a Lorentz-invariant, transparent universe. Our results are consistent with all other measures of transparency to date. This is in part because they are not extremely precise. Our Tolman test also assumes that the measurements of the SNeIa and of the BAF are not affected by systematic biases with magnitudes that are a significant fraction of the magnitudes of the uncertainties. Our test is limited by the precision of the BAF measurement and the redshift range over which it has been measured. As we have shown, experiments planned and underway will increase the redshift range and improve the overall precision by an order of magnitude.

The most precise transparency measurements at visible wavelengths today are statistical angular difference measurements, which can only constrain attenuation correlated with specific types of absorbing structures in the universe (*e.g.*, MgII absorbers, Ménard *et al.* 2008; clusters of galaxies, Bovy *et al.* 2008). The simple Tolman test performed here limits the full, unclustered, line-of-sight attenuation between two redshifts.

The technique used in this paper provides a test of transparency that is not very sensitive to astrophysical assumptions, both because the BAF has a straightforward origin during an epoch in which growth of structure is linear and the dominant physics is well understood, and because

there is no significant “evolution” with cosmic time for which we must account. This is in contrast to other methods for measuring angular diameter distances and brightnesses, where there are no precisely “standard” rulers, and evolution is dramatic with redshift. On the other hand, the ultimate precision of any test of this type may come from the finite comoving volume in the observable universe. Cosmic variance will dominate the BAF error budget eventually.

The SNeIa samples have been corrected as best as possible for line-of-sight extinction by fitting an empirical correlation of extinction with a change in color. However, there are a few problems with this approach. First, this approach cannot correct for “gray” dust (Aguirre 1999). Second, this approach can also not correct for a monopole component; it only corrects for components that show variations around the mean level. Third, these corrections will be wrong or fooled if there are intrinsic relationships between color and luminosity for SNeIa. Fourth, the empirical corrections found by these projects tend to be odd in the context of what is expected from the reddening and attenuation by dust in the Milky Way (Jöeveer 1982; Conley *et al.* 2007; Ellis *et al.* 2008; Nobili & Goobar 2008). The Tolman test is sensitive to any kind of absorber and makes no assumptions about the wavelength dependence or fluctuations of the opacity. Given that the SNeIa results have been corrected for a color–brightness relation, the test presented here looks at the mean opacity toward SNeIa of the fiducial color to which the compiled SNeIa have been corrected.

The best-fit value of $\Delta\tau$ obtained from our analysis is negative, i.e., SNeIa are brighter than expected from the angular diameter distance measurements using the BAF. A conversion of dark sector particles into photons could provide a physical explanation for this result. However, this could also indicate the presence of a systematic bias in either the SNeIa or BAF experiments. A test such as the one presented in this paper is a useful tool to bring such biases to light.

At present, because the differences among competitive world models are not large over the redshift range $0.20 < z < 0.35$, our test is not yet sensitive enough to rule out extreme axion or “gray” dust models that reconcile SNeIa results with an Einstein-de Sitter universe by using effective opacity to adjust the inferred redshift–luminosity-distance relation. However, these models will all be severely constrained within the next few years (see also Corasaniti 2006).

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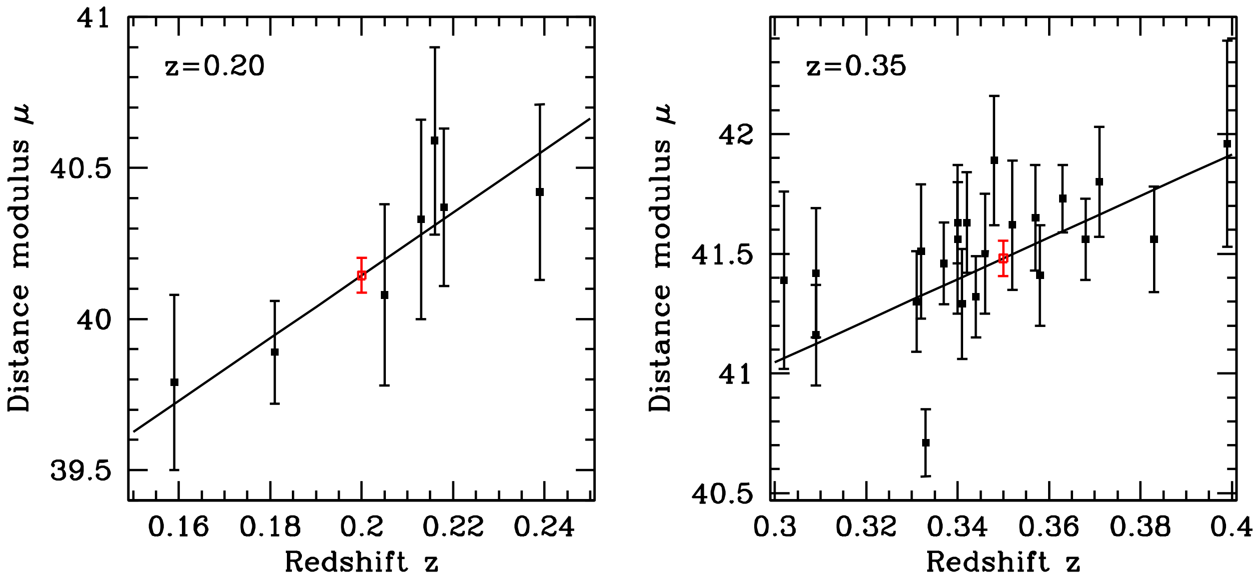

Fig. 1.— Distance-modulus–redshift relation. Filled black squares with uncertainty bars show the SNeIa data (from Davis *et al.* 2007) used in Samples A (left panel) and B (right panel). Open red squares show the distance moduli $DM(0.20) = 40.14 \pm 0.06$ and $DM(0.35) = 41.48 \pm 0.07$ (68% confidence) inferred from the fits to the data.

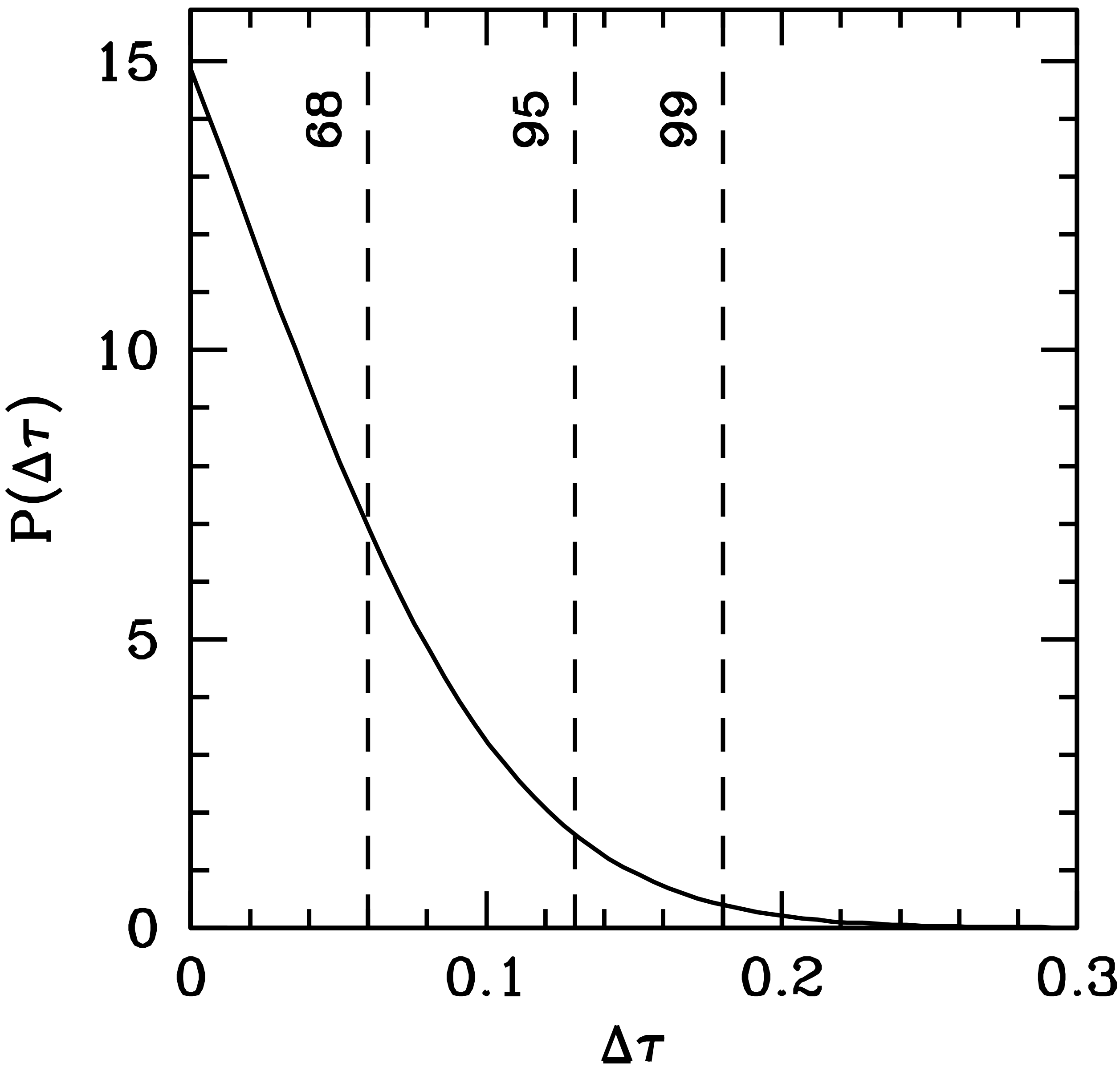

Fig. 2.— Posterior distribution of $\Delta\tau$ between $z = 0.35$ and $z = 0.20$ obtained from the Bayesian analysis described in Section 2. The 68, 95 and 99% confidence upper limits are indicated by the corresponding dashed lines.